Hawaii Solar Integration Study: Solar Modeling Developments and Study Results

Preprint

R. Piwko
GE Energy

L. Roose
Hawaii Natural Energy Institute

K. Orwig
National Renewable Energy Laboratory

M. Matsuura
Hawaiian Electric Company

D. Corbus
National Renewable Energy Laboratory

M. Schuerger
Energy Systems Consulting Services

Presented at the 2nd Annual International Workshop on Integration of Solar Power into Power Systems Conference
Lisbon, Portugal
November 12–13, 2012

This research work is jointly sponsored and funded by the U.S. Department of Energy, the Hawaii Natural Energy Institute, and the Hawaiian Electric Company.

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Conference Paper
NREL/CP-5500-56311
December 2012

Contract No. DE-AC36-08GO28308

Available electronically at http://www.osti.gov/bridge

Available for a processing fee to U.S. Department of Energy
and its contractors, in paper, from:

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone: 865.576.8401
fax: 865.576.5728
email: mailto:reports@adonis.osti.gov

Available for sale to the public, in paper, from:

U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
phone: 800.553.6847
fax: 703.605.6900
email: orders@ntis.fedworld.gov
online ordering: http://www.ntis.gov/help/ordermethods.aspx

Cover Photos: (left to right) PIX 16416, PIX 17423, PIX 16560, PIX 17613, PIX 17436, PIX 17721

Printed on paper containing at least 50% wastepaper, including 10% post consumer waste.

Hawaii Solar Integration Study: Solar Modeling Developments and Study Results

Richard Piwko, Leon Roose, Kirsten Orwig, Marc Matsuura, David Corbus, Matt Schuerger

***Abstract*—The Hawaii Solar Integration Study (HSIS) is a follow up to the Oahu Wind Integration and Transmission Study (OWITS) completed in 2010. HSIS examines the impacts of higher penetrations of solar energy on the electrical grid, focusing on impacts to the operation of the bulk power transmission system and other interconnected generation resources. Issues specific to generation resource interconnection (normally the subject of a generator interconnection requirements study) and distribution system impacts of high distributed solar penetration scenarios were not the focus of the study. HSIS goes beyond the island of Oahu and investigates Maui as well. The study examines reserve strategies, impacts on thermal unit commitment and dispatch, utilization of energy storage, renewable energy curtailment, and other aspects of grid reliability and operation. For the study, high-resolution (2-second) solar power profiles were generated using a new combined Numerical Weather Prediction (NWP) model / stochastic-kinematic cloud model approach, which represents the "sharp-edge" effects of clouds passing over solar facilities. As part of the validation process, the solar data was evaluated using a variety of techniques including: wavelets, power spectral densities, ramp distributions, extreme values, and cross correlations. This paper provides an overview of the study objectives, results of the solar profile validation, and results for the Oahu portion of the study.**

Keywords- Wind, solar, integration studies, reserves, renewable energy.

I. INTRODUCTION

The Hawaii Solar Integration Study (HSIS), a follow up to the Oahu Wind Integration and Transmission Study (OWITS) completed in 2010, focuses on the operating impacts of higher penetrations of solar energy on the Oahu and Maui bulk power systems. The studies support the Hawaii Clean Energy Initiative (HCEI), announced in January 2008, which includes a commitment to achieve 40% renewable generation from clean energy by 2030, expanded distributed generation, and load reduction. The HSIS study objectives are:

1. Analyze the Oahu and Maui bulk power systems with high penetrations of solar (and wind) generation and a) assess the levels of solar/wind energy delivered for a range of distributed/centralized photovoltaic (PV) plant scenarios, b) assess curtailment impacts, c) identify the operating characteristics (commitment, dispatch), d) assess the dynamic performance, e) identify the operational and reliability challenges across the range of operational timeframes.
2. Identify operational/mitigation strategies and new technologies that could help enable high penetrations of wind and solar power.
3. Assess the impact of each mitigation approach across the range of operational timescales; and
4. Recommend mitigation strategies and requirements to increase wind and solar energy delivered, reduce adverse impacts on the thermal units, and ensure reliable and cost conscious system operation.

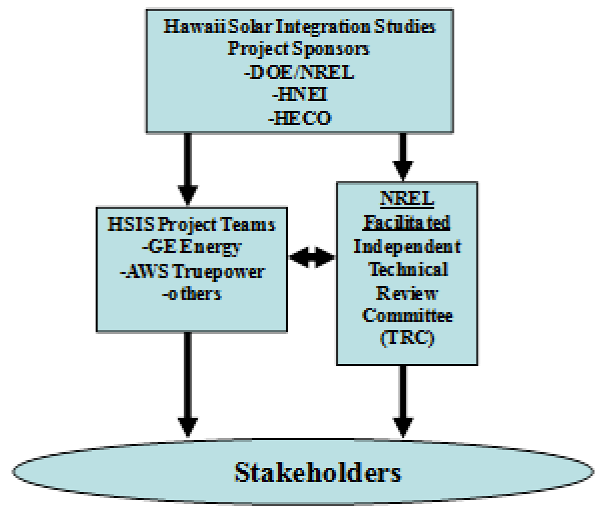

Figure 1. Organization of the HSIS.

The HSIS was jointly sponsored by the Hawaii Natural Energy Institute (HNEI), the U.S. Department of Energy (DOE), and the Hawaiian Electric Company (HECO); see Figure 1. The National Renewable Energy Laboratory (NREL) convened and facilitated a Technical Review Committee (TRC), comprised of a diverse group of technical experts, for the study. The primary focus of the TRC was technical review of HSIS study work including methods, assumptions, and preliminary results.

II. OVERVIEW OF OAHU GRID

HECO is a vertically integrated investor-owned electric utility with two wholly-owned subsidiary utilities, Maui Electric Company, Ltd. (MECO), and Hawaii Electric Light Company, Inc. (HELCO). HECO's service territory is the island of O`ahu, with MECO serving the county of Maui (Maui, Lana`i and Moloka`i islands), and HELCO serving Hawai`i Island. Together, HECO and its subsidiaries serve 95% of the State of Hawaii's 1.2 million residents. There are no transmission interconnections between the islands so each island's generating system must stand alone without backup from its neighbor island utility grids. Further, without indigenous conventional fuel resources such as oil, coal and natural gas, Hawaii imports most of its energy resources, the vast majority of which is oil. Not surprisingly, Hawaii has among the highest electricity rates in the United States.

The island of Oahu measures 44 miles long and 30 miles across and is the most populated of the 7 main Hawaiian Islands. The capital of Hawaii, Honolulu, is located on the southeast shore of Oahu as is the popular vacation destination of Waikiki. Today, system peak power demand on the island of Oahu is between 1100 MW to 1200 MW, with a system minimum demand between 550 and 700 MW. For the HSIS study year of 2015, Figure 2 shows the projected average daily load profile assumed for Oahu.

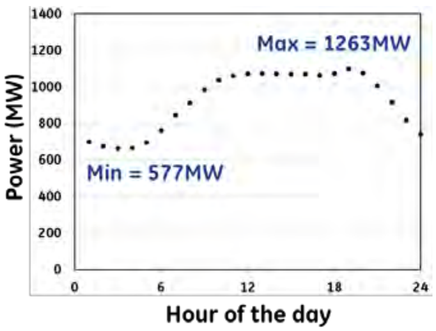

Figure 2. Projected average daily load profile for Oahu in year 2015.

The majority of the firm capacity generation on the island is located on the west side, and includes the utility owned Kahe and CIP power stations as well as plants owned and operated by independent power producers AES, Kalaeloa and HPower. Two additional utility owned power stations, Waiau and Honolulu, are located near Pearl Harbor and downtown Honolulu respectively.

Oahu is presently served by a firm capacity generating fleet that totals 1,817 MW, about 81% of which is oil-fired. A summary of the generation resources on the island is provided below.

Firm generating capability (as of August, 2012):

HECO power plants
Honolulu (Steam, Cycling, Oil).......................113 MW
Waiau (Steam, Baseload, Oil)..........................186 MW
Waiau (Steam, Cycling, Oil)............................211 MW
Waiau (CT, Peaking, Oil)................................103 MW
Kahe (Steam, Baseload, Oil)............................650 MW
CIP (CT, Peaking, Biodiesel)...........................120 MW

Independent power producers
HPower (Steam, Baseload, Waste-to-energy)...46 MW
Kalaeloa (Combined-cycle, Baseload, Oil)......208 MW
AES (Steam, Baseload, Coal)...........................185 MW

Total firm generating capability….........1,817 MW

Non-firm generation (as of August, 2012):

Kahuku Wind Farm..30 MW
Distributed PV………………………………....80 MW
Utility-scale PV……………………………….....1 MW

Total non-firm generation …....................111 MW

Moreover, in addition to the continued strong growth in new distributed PV installations on Oahu, the following new utility-scale renewable energy generating plants totaling more than 100 MW nameplate are in progress to be commissioned on the HECO grid by year-end 2012.

HPower Expansion …….………………………27 MW
Kawailoa Wind Farm ....69 MW
Utility-scale PV ……………...............................5 MW

Energy produced by firm capacity generating resources located in the west is transmitted to load centers in the east via 138kV transmission lines. The 138kV transmission circuits deliver energy to 46kV sub-transmission circuits, which in turn are tied to distribution circuits at 25kV, 12kV and 4kV. The majority of the distribution circuits on Oahu operate at 12 kV. Figure 3 is an island map showing the general locations of:

- Utility scale generation sites
- 138kV transmission corridors
- High load density areas
- Transmission areas nearing capacity limits per HECO planning criteria

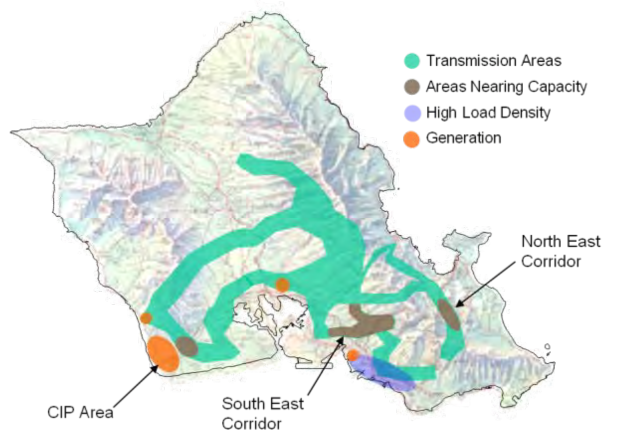

Figure 3. HECO generation sites and 138kV transmission corridors.

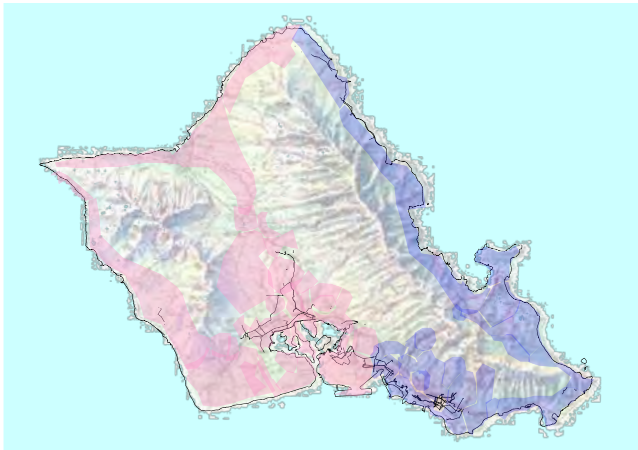

Figure 4. HECO 46kV subtransmission circuits and customer load areas.

Figure 4 shows the general locations of HECO's 46 KV sub-transmission circuits and the load areas served on Oahu. The blue shaded area indicates that more than one-half (56%) of HECO's total system load is located on the eastern portion of the island. Generally, customer loads located in the northern part of the island and along the coastal regions are served by HECO's 46 KV sub-transmission circuits which have a significantly lower power flow capability compared to 138 KV transmission circuits.

III. Oahu Study Scenarios

The HSIS Oahu system study scenarios focus on the operating impacts of higher penetrations of solar energy on the Oahu bulk power systems, building upon high wind penetration scenarios evaluated in the 2010 OWITS analyses. The HSIS analyzed and assessed the Oahu grid operations and the levels of PV/wind energy delivered for a range of both distributed and centralized PV plant scenarios. The scenarios evaluated are identified in Table 1 below.

TABLE I. Study Scenarios for oahu Power Grid

Scenario	Dist PV	Central PV	Oahu Wind	Off-Island Wind	Total
Baseline	60MW	-	100MW	-	160MW
3A	260MW	100MW	100MW	-	460MW
3B	160MW	200MW	100MW	-	460MW
4A	360MW	400MW	100MW	-	860MW
4B	160MW	200MW	100MW	200MW	660MW

In each of the scenarios, 100 MW of wind energy located in the northern region of Oahu was included to represent the wind plants presently in service and scheduled for commercial operation by year-end 2012. A scenario (Scenario 4B) evaluating additional wind energy produced by a proposed 200 MW wind plant located on a neighbor island and transmitted via submarine cable to the Oahu grid was also included.

Scenarios of high penetration distributed and central PV were then layered on these high wind scenarios. Four basic scenarios were developed. Scenario 1 included a total of 100MW of additional distributed and central station PV. Scenario 2 included a total of 200MW of additional distributed and central station PV. In Scenarios 3A and 3B, a total of 360 MW of total PV generation was evaluated in both cases, with the respective levels of distributed/central PV varied to distinguish the impact to grid operation of more or less PV of distributed versus central plant characteristics tied to the system. In Scenario 4A, the level of total PV was increased substantially to 760 MW to evaluate grid operation and cost impacts at a very high PV penetration level, with a fairly even split of distributed and central plant PV modeled. Scenario 4B has the same level of annual wind+solar energy as 4A, but the generation portfolio has 400 MW less solar resources and 200 MW more wind resources. Upon completing analysis of the Baseline case, Scenario 3A was analyzed next and based on the results, the project sponsors determined that an analysis of lower PV penetration levels in Scenarios 1 and 2 were not of high value interest and further analyses proceeded directly to Scenarios 3B, 4A and 4B.

IV. Solar Data Development and Validation

Solar power production profiles are modeled to represent future potential installations and penetrations. For integration studies, there are several key characteristics of the solar power production profiles that are essential to simulate realistic production profiles, as detailed in Orwig et al. [1]. These characteristics include:

- Representative variability at all timescales, i.e. ramp behavior
- Spatial correlation, both intra-plant and plant-to-plant
- Temporal correlation
- Capacity factor

Synthetic solar power forecasts are also generated to replicate real-time operational solar power forecasts that grid operators might use for unit commitment, dispatch, reserves allocations, transmission congestion, etc. The error distributions of the synthetic forecasts should be representative of those of the real-time operational forecasts.

Misrepresentations of any of these characteristics could cause unrealistic simulations of power production operations, grid impacts, and associated costs. Therefore, the data generated for this study went through a rigorous development and validation process to minimize the uncertainty.

AWS Truepower generated the solar power production profiles using a Numerical Weather Prediction (NWP) model coupled with a stochastic-kinematic cloud model. The model is able to generate and dissipate clouds over time, and advects them through time and space at a 1-s time resolution. The NWP model drives the cloud movement, while the cloud model drives the evolution. More details of this coupled model can be found in M. Brower et al. [2].

The data created consisted of 2-s solar power production profiles for central and distributed PV systems for 2007-2008, the penetrations of which are described in Section III. The data was validated by verifying the ramp characteristics (also discussed in Section V), correlations, distributions, and extreme values. The validation process is shown in Figure 5. The details of these results are pending publication as an NREL technical report.

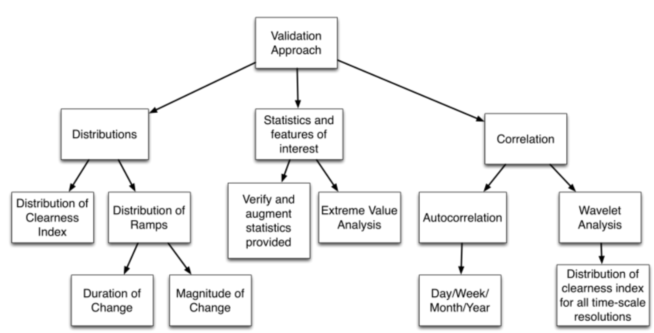

Figure 5. Schematic of data validation process.

An example of the validation is the distribution of the clearness index between measured and modeled irradiance, as shown in Figure 6. The verification was done for May 2010, when recorded observations were available. The figure demonstrates that the distributions are very similar, indicating that the proportional amount of cloud cover to clear sky of the modeled data is realistic.

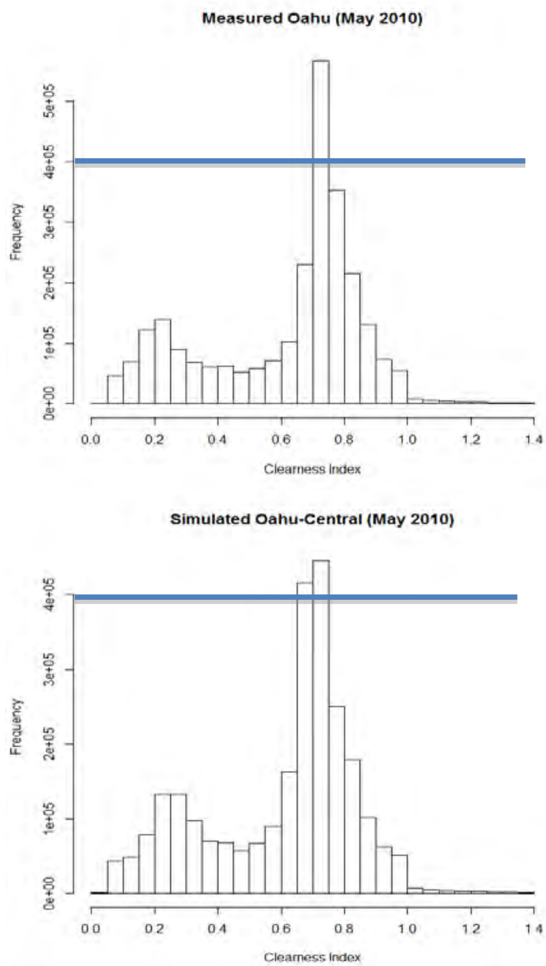

Figure 6. Frequency distribution of measured (top) and modeled (bottom) clearness index on Oahu. Blue horizontal line is for scale reference.

V. Solar Integration Study Results - Oahu

A. *Variability in Wind/Solar Power Generation*

The output of an individual solar generation facility is highly variable. Output can change from 100% to 20% within 1-2 minutes when a cloud passes over. Variations in power output of a single PV facility can cause troublesome local voltage variations on its interconnected feeder. Furthermore, the aggregate variability of all PV facilities connected to the Oahu grid introduce new operational challenges for grid operators and the thermal generation fleet. Given that generation and load must always be balanced, the thermal fleet must ramp up and down to follow all variations in wind, solar, and load. In addition, the thermal fleet (and possibly storage systems or demand response) must provide sufficient reserves to cover sustained drops in wind and solar power output so that grid frequency is maintained at 60 Hz.

Figure 7 shows the variability in output of aggregate wind and solar resources for Scenarios 4A (dominated by solar PV) and 4B (mix of solar and wind). Variability is shown for time periods of 5, 10, 30 and 60 minutes. The horizontal axis is scaled in per-unit of the aggregate wind+solar resource rating (860 MW for 4A and 660 MW for 4B). Table II summarizes the worst-case drops in aggregate wind and solar power output over the four different time periods. This data indicates that Scenario 4B has significantly lower aggregate variability than Scenario 4A, which implies a lower requirement for system operating reserves.

TABLE II. Worst-Case variability for Scenarios 4A and 4B

	Scenario 4A	Scenario 4B
Worst 5-min drop	-186 MW	-132 MW
Worst 10-min drop	-183 MW	-143 MW
Worst 30-min drop	-308 MW	-219 MW
Worst 60-min drop	-399 MW	-324 MW

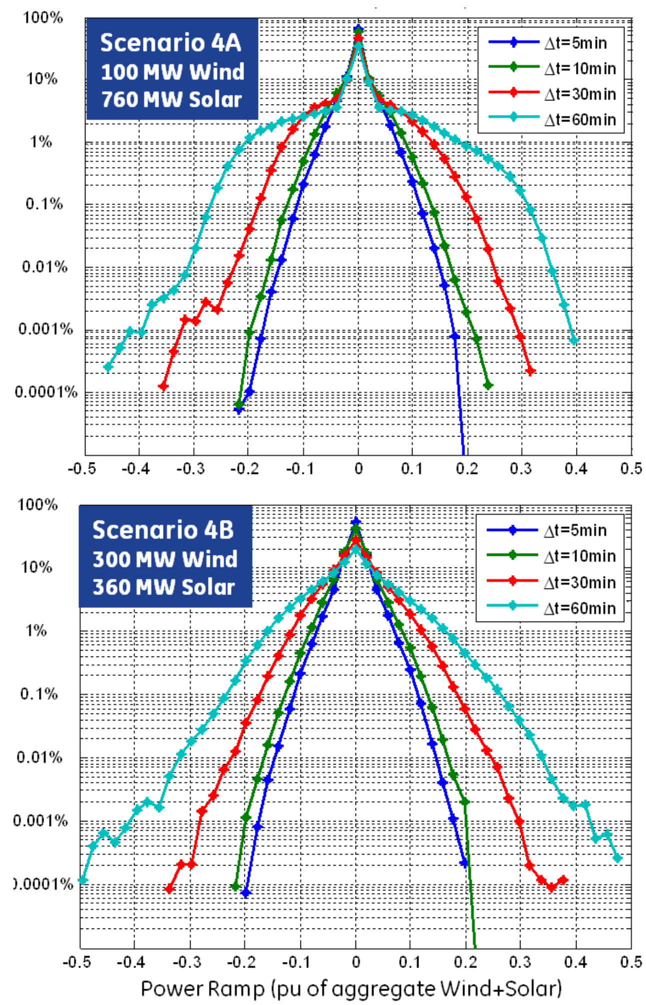

Figure 7. Variability in aggregated wind and solar power output for Scenarios 4A and 4B

B. *Spinning Reserve Requirements*

The vast majority of Oahu's electrical energy is generated by a group of thermal power plants fueled predominantly by oil and coal. Historically their operation was dominated by following the daily load pattern and providing contingency reserves.

Being an island system with no interties to neighboring power grids, Oahu's planning and operating criteria is to always carry sufficient contingency reserves to completely cover loss of the largest single generating unit on-line (typically the 185 MW coal plant). Spinning reserves to cover variability in wind and solar generation must be separate from contingency reserves, so that down-ramps in wind and solar generation do not compromise the grid's ability to survive loss of a large thermal generator.

To accomplish this, the study assumes the total reserves are separated into two categories; contingency reserves (to cover loss of generating unit) and operating reserves (to cover variability in wind and solar output). Contingency reserves are all spinning reserves, as they must respond immediately to a loss of generation event. Operating reserves are comprised of both spinning and non-spinning reserves, considering that wind and solar variations occur over multiple timescales. The following discussion focuses on the spinning portion of operating reserves.

A criteria was developed so that the grid would have sufficient operating reserves to cover wind and solar variability 99.99% of time periods without dipping into contingency reserves. During daytime hours, operating reserves need to cover variability from both wind and solar resources. During nighttime hours solar generation is offline so only wind variability is relevant.

Figure 8 shows the spinning portion of operating reserves for the study scenarios during daytime hours, as a function of how much wind and solar power is being delivered to the grid. Scenario 4A, with 760 MW of PV generation capacity, requires the most spinning reserves (240 MW when wind and solar generation exceeds 300 MW). The figure shows that other scenarios require significantly less operating reserves during daytime hours,

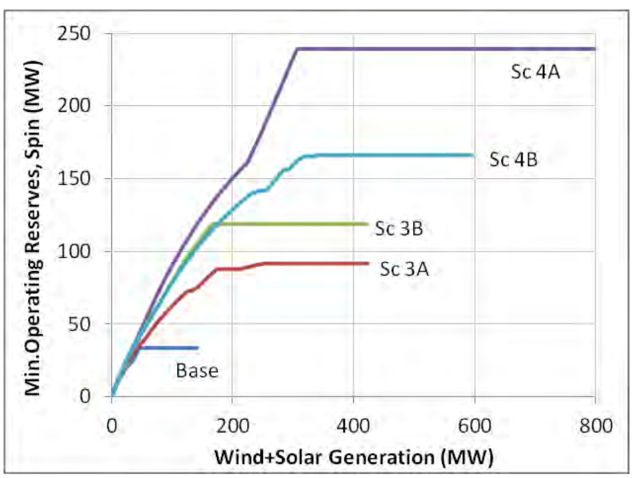

Figure 8. Operating reserve requirements, spinning, daytime hours.

Figure 9 is a similar plot for nighttime hours, when solar generation is offline. Scenario 4B has 300 MW of wind generation and requires approximately 105 MW of spinning reserves when wind generation exceeds 120 MW. The other scenarios have only 100 MW of wind generation and nighttime spinning reserve requirements are below 35 MW.

These reserve requirements are based solely on capacity reserve requirements and will need to be verified by the dynamic response and frequency impact assessment to be done later in the study.

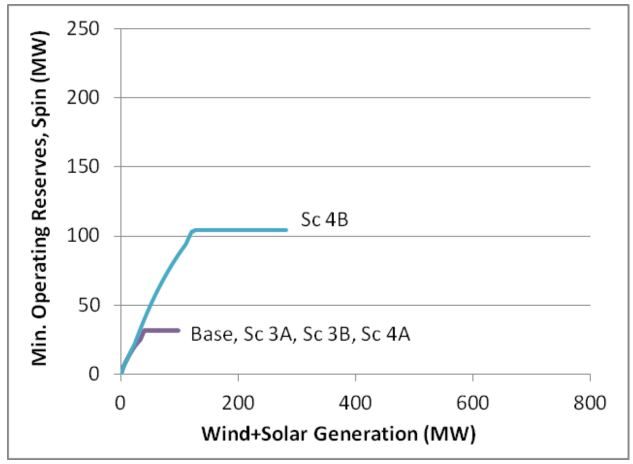

Figure 9. Operating reserve requirements, spinning, nighttime hours.

C. *Impacts on Generation Commitment and Dispatch*

Annual hourly operation of the Oahu power grid was simulated using the GE-MAPS production simulation program. Input data accounted for thermal generation operating characteristics (fuel costs, start time, ramp rate, etc.), hourly system load profiles, wind/solar generation profiles, 4-hour-ahead wind/solar forecasts, and operating/contingency reserves as described previously. Table III shows the contributions of thermal, wind, and solar generation resources to serving Oahu's annual load energy. Scenarios 3A and 3B both have 360 MW of solar generation, but 3B has a much high percentage of solar in central plants, including two plants rated 100 MW each. The central solar plants are assumed to use single-axis tracking and therefore have higher capacity factors (22%) than distributed rooftop solar resources (18%). Scenarios 4A and 4B have roughly the same available energy from wind and solar resources (about 1640 GWh, or 20.3% of load energy). However, not all of the wind and solar can be accommodated by the grid and curtailment is required, reducing the load-serving contribution of wind+solar to 19.2% in Scenario 4A and 19.5% in Scenario 4B.

TABLE III. GENERATION ENERGY BY TYPE FOR STUDY SCENARIOS

	Base	3A	3B	4A	4B
Thermal	95.1%	88.8%	88.5%	80.8%	80.5%
Wind	3.7%	3.7%	3.7%	3.7%	11.7%
Solar	1.2%	7.5%	7.8%	15.5%	7.8%
Wind+Solar	4.9%	11.2%	11.5%	19.2%	19.5%
Note: Annual load energy is 8084 GWh for all Scenarios.					

Figure 10 shows duration curves of hourly wind and solar energy penetration for the study scenarios. Scenarios 3A and

3B with 360 MW solar and 100 MW wind generation have maximum hourly energy penetrations near 30%; i.e., 30% of load energy is served by wind+solar generation in some hours of the year. Scenario 4A (760 MW solar & 100 MW wind) has a maximum hourly wind+solar penetration of 50%. Scenario 4B reaches 45% hourly penetration.

One significant observation is the distinct bimodal nature of the duration curve for Scenario 4A. This scenario is dominated by solar generation, so there is a distinct difference in the magnitude of wind+solar energy penetration for day and night.

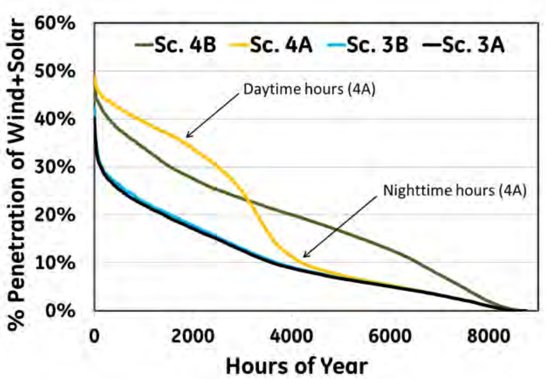

Figure 10. Duration curves of hourly wind+solar energy penetration.

D. *Wind and Solar Utilization and Curtailment*

One objective of the study was to find "pain points" in PV penetration, where the amount of PV generation would challenge the existing operational capabilities of the Oahu power grid. One measure of "pain" is curtailment, which occurs when the grid is not able to accept all the wind and solar energy that is available during some hours of the year. Figure 11 shows annual wind and solar energy delivered and curtailed for each study scenario. In scenarios 3A and 3B (460 MW wind+solar), all the available wind and solar energy is accommodated by the grid. In Scenarios 4A and 4B, however, there are time periods when some of the wind and solar energy must be curtailed. Both scenarios have about 1640 GWh of total wind+solar energy available in a year. In Scenario 4B 85 GWh is curtailed and in Scenario 4B 70 GWh is curtailed.

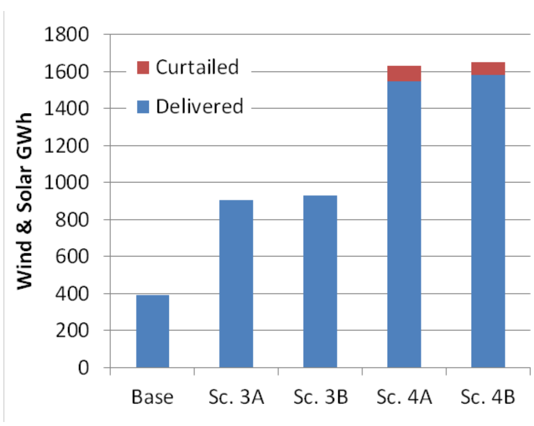

Figure 11. Wind+solar energy delivered and curtailed.

Figure 12 shows the annual curtailed wind+solar energy by hour of day. Scenario 4A is dominated by 760 MW of solar generation. Curtailment occurs during daytime hours when solar generation is high and spinning reserve requirements are also high (185 MW contingency reserve plus 240 MW operating reserve). Scenario 4B has a balance of wind and solar generation. Overall curtailment is lower (70 GWh vs. 85 GWh), and curtailment occurs primarily during nighttime hours when load is low and thermal generating plants are operating near minimum power limits holding adequate down-reserves.

These levels of wind and solar curtailment are based on the assumption that Oahu thermal generation carries 90 MW of down-reserves to respond to loss-of-load events. Further investigation of Oahu grid operations indicated that 140 MW of down-reserves would likely be required during daytime hours, which would approximately double the amount of wind and solar energy curtailed in Scenario 4A. Curtailment in Scenario 4B would not be significantly affected with the higher level of daytime down-reserves.

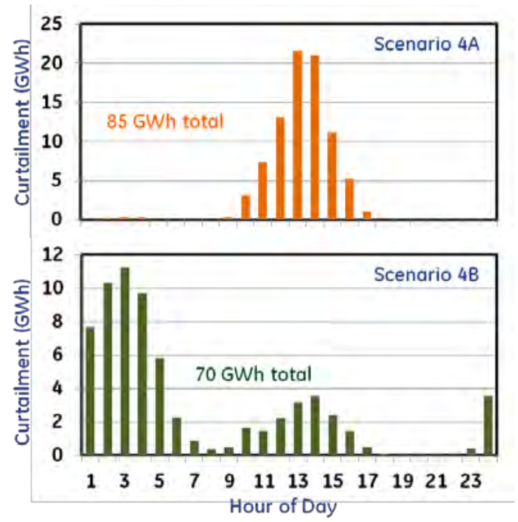

Figure 12. Wind+solar curtailment by hour of day.

E. *Impacts on Operation of Baseload Generation*

As penetration of wind and solar power increase, thermal generating resources are operated at reduced power levels. During periods of high wind and solar output, some thermal generating units will need to operate at minimum power. Although some units can be decommitted, others must remain online to provide spinning reserves and/or other ancillary services.

Table IV shows the number of hours in a year that the Oahu baseload generating units operate at minimum load for each of the study scenarios. As the penetration of wind and solar generation increases, the number of hours at minimum load for Oahu baseload units increases dramatically. In Scenarios 4A and 4B, several units operate at minimum load for more than 6000 hours in a year. The operations and maintenance impact of operating baseload generation at this low level for the number of hours shown will need to be assessed and could impact the results, but is not within the scope of this study.

TABLE IV. ANNUAL HOURS AT MINIMUM LOAD FOR OAHU BASELOAD GENERATING UNITS

Hours at min dispatchable power (respecting effective down reserve)	SCENARIO				
	Base (40MW)	3A (40MW)	3B (40MW)	4A (90MW)	4B (90MW)
AES Coal	168	170	171	1512	1398
KalaeloaCC	272	272	272	1149	1962
Kahe 1	2373	3179	3439	6902	7167
Kahe 2	3161	4627	5004	6699	6983
Kahe 3	967	1202	1270	3605	3549
Kahe 4	1160	1552	1642	4703	4692
Kahe 5	457	554	602	2615	2575
Kahe 6	1516	2021	2152	5577	5532
Waiau 7	2464	3268	3503	7302	7616
Waiau 8	570	746	796	4640	4626

F. *Non-Synchronous Generation Sources*

With increasing penetration of wind and solar generation, thermal generation is displaced during many hours of the year. When thermal generators are decommitted, the system loses the contributions of their synchronous machines to voltage support and maintaining the short-circuit level of the grid. One way to quantify this effect is to calculate the percentage of non-synchronous generation that is connected to the grid in each hour of the year. Duration curves showing the percentage of non-synchronous generation on the Oahu grid for the study scenarios is shown in Figure 13. All curves have a distinct bimodal shape, where the left portion is dominated by daytime hours when solar PV generation is online, and the right portion is dominated by wind generation alone during nighttime hours. Scenario 4A (760 MW PV and 100 MW wind) exceeds 50% non-synchronous generation during a few hours of the year.

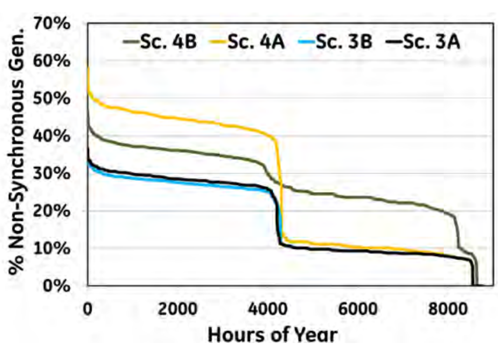

Figure 13. Duration curve of percent nonsyschronous generation.

G. *Challenging Periods for Grid Operations*

The results of the annual hourly production cost simulations were screened to identify challenging time periods for grid operation. The screening criteria are shown below:

- Wind and solar power can drop in a sustained fashion in 10-20 minutes. This challenges ramp rate capability of thermal units.
- Wind and solar power can drop in a sustained fashion in 30-60 minutes. This consumes up-reserve and requires use of quick-start units.
- Wind and solar power can rise when thermal units are near min power. This consumes down-reserves.
- Wind and solar power can vary its production rapidly within an hour. This challenges the ramp rate and maneuvering capability of thermal units.
- Load rejection event could occur when thermal units are backed down. Transient response could reduce generator power below stable minimum point.
- A large thermal generator or HVDC converter can trip when the system is low on reserves. This triggers under-frequency events and could cause distributed rooftop PV to trip and possibly load-shedding.

Each of these screening criteria identified specific hours when the Oahu grid would be in unfavorable operating conditions to survive each type of event. For worst-case conditions, dynamic simulations were performed to quantify the overall system response and to determine if the system could survive with adequate reliability margins. A representative simulation for the most severe loss of generation event is shown below.

H. *Frequency Response for Generation Trip Event*

System risk for a loss of generation event is most severe when system up-reserves are low, the percentage on non-synchronous generation is high (i.e, system inertia is low), and distribution-connected rooftop PV output is high. An hour was identified to meet this criteria and loss of a 185 MW coal unit was simulated using PSLF. Before the disturbance, system load was 1176 MW, total wind and solar generation was 358 MW of which 178 MW was from distribution-connected PV. The system frequency response is plotted in Figure 14. Note that this simulation did not take into account the automatic under frequency load shed protection that is currently in place.

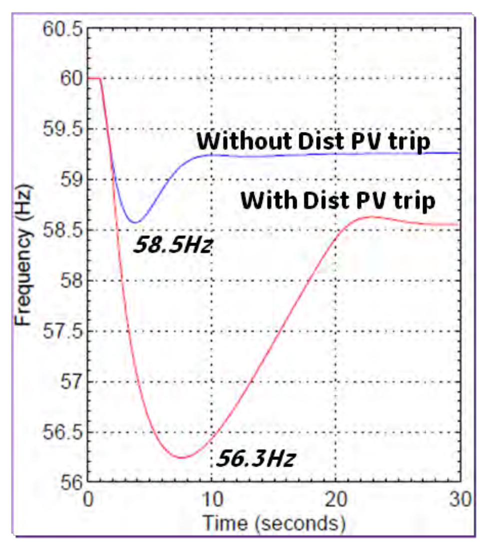

Figure 14. System frequency following trip of 185 MW thermal generator, without underfrequency load shedding.

If all the wind and solar generation stays on line after the event (i.e., is equipped with frequency ride-through capability), the system frequency dips to 58.5 Hz in about 4 seconds and then begins to recover, per the blue trace. If the distribution-connected PV is assumed to be compliant with IEEE standard 1547, it would trip off line when the frequency falls to 59.3 Hz. The red trace shows that if the distribution-connected PV trips, another 178 MW of generation is lost and system frequency declines to 56.3 Hz. This illustrates that island systems like Oahu would face significant system impacts if the penetration of 1547-compliant PV resources becomes too large.

VI. Conclusions

Although this study is still under way, results to date have substantiated several significant conclusions.

The Oahu bulk power system can accommodate the 100 MW wind and 360 MW PV solar generation modeled in the study without significant modifications to existing system-level operating practices beyond carrying additional spinning reserves. The level of wind and solar resources are capable of serving a little more than 11% of Oahu's annual load energy. The majority of impacts with this penetration level are expected to be at the individual feeder level, where voltage variations and reactive power management will need to be studied and engineering solutions developed to address any issues that are identified.

Two study scenarios evaluated grid operation with wind and solar resources capable of supplying approximately 20% of Oahu's annual load energy (Scenario 4A: 760 MW PV and 100 MW wind; Scenario 4B: 360 MW PV and 300 MW wind). With this level of wind and solar penetration, high levels of operating reserves are required to cover the variability/uncertainty of wind/solar power output. Up to 10% of the wind and solar energy would need to be curtailed assuming grid operating practices and thermal plant capabilities remain the same as they are now. Curtailment can potentially be decreased, emissions can be reduced, and overall system operating efficiency can be increased by the following measures, however these mitigation measures have not been fully assessed in the study to date:

- Modifying operating practices (e.g., changing must-run schedules for baseload thermal units);
- Improving the operational flexibility of selected thermal plants (e.g., reducing minimum power limits and increasing ramp rates);
- Reducing spinning reserves on thermal units by using other sources of reserves (e.g., battery energy storage systems, load control); and
- Having wind/solar resources participate in grid dispatch and ancillary services (e.g., down-reserves from wind/solar plants).

The Oahu grid is capable of surviving the most severe loss of generation contingency, even with high penetrations of wind and solar resources. However, this assumes that the wind and solar resources are capable of riding through transient low-frequency events. If a significant portion of the solar resources are distribution-connected rooftop systems that are compliant with IEEE Standard 1547, then there is increasing likelihood that loss of a large thermal plant would trigger underfrequency tripping of rooftop solar resources, compounding the severity of the contingency. This could, in turn, trigger increased levels of underfrequency loadshedding to arrest the decline in frequency – a critical issue for island systems where frequency is inherently more variable than in larger interconnected grids. This analysis has highlighted 1547-compliant solar PV as a potential risk to the system, should the penetration of such resources become sufficiently large. Subsequent analysis is required to better quantify the impacts, including coordination with loadshedding schemes. IEEE Standards Coordinating Committee 21 has recognized the grid reliability risks associated with underfrequency PV tripping and has reconvened to discuss revisions to Standard 1457 [4].

HECO has implemented rules that require distribution-connected PV inverters to have adjustable underfrequency ride-through capability, set to withstand underfrequency events down to 57 Hz for 300 cycles. For frequency excursions below 57 Hz or above 60.5 Hz, the inverters must disconnect in 10 cycles.

There is still more work to be done as the penetration renewable resources in Hawaii continues to grow and the mix of resources continues to evolve. Future work includes more analysis of loadshedding performance, dynamic performance analysis for challenging time periods, distribution-level interconnection issues, and the impacts of running thermal generation at low power levels for extended periods.

Authors and Affiliaions

Richard Piwko, GE Energy Consulting, Schenectady, New York USA.

Kirsten Orwig & **David Corbus**, National Renewable Energy Laboratory, Golden, Colorado, USA.

Matt Schuerger, Energy Systems Consulting Services LLC, St. Paul Minnesota, USA.

Marc Matsuura, Hawaiian Electric Company, Honolulu, Hawaii, USA.

Leon Roose, Hawaii Natural Energy Institute, Honolulu, Hawaii, USA.

References

[1] K. Orwig, M. Hummon, B-M Hodge, D. Lew, "Solar Data Inputs for Integration and Transmission Planning Studies," in 1st Int. Workshop on the Integration of Solar Power into Power Systems, Aarhus, Denmark, 2011.

[2] M. Brower, P. Beaucage, J. Frank, "Development of a Cloud Model to Generate High-Frequency Solar Irradiance and Power Data", 2nd International Workshop on Integration of Solar Power into Power Systems, Paper SIW12-48, Lisbon, Portugal, November 12-13, 2012.

[3] Hawaii Natural Energy Institute, Hawaiian Electric Company, General Electric Compaly, "Oahu Wind Integration Study", pdf available at www.hnei.hawaii.edu, February 2011.

[4] SCC21 Home Page, http://grouper.ieee.org/groups/scc21/dr_shared/